



# **PC UFC Briefing September 21-22, 2004**

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## **PC UFC Design Strategies-- Tie Forces and Alternate Path**

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# Tie Forces



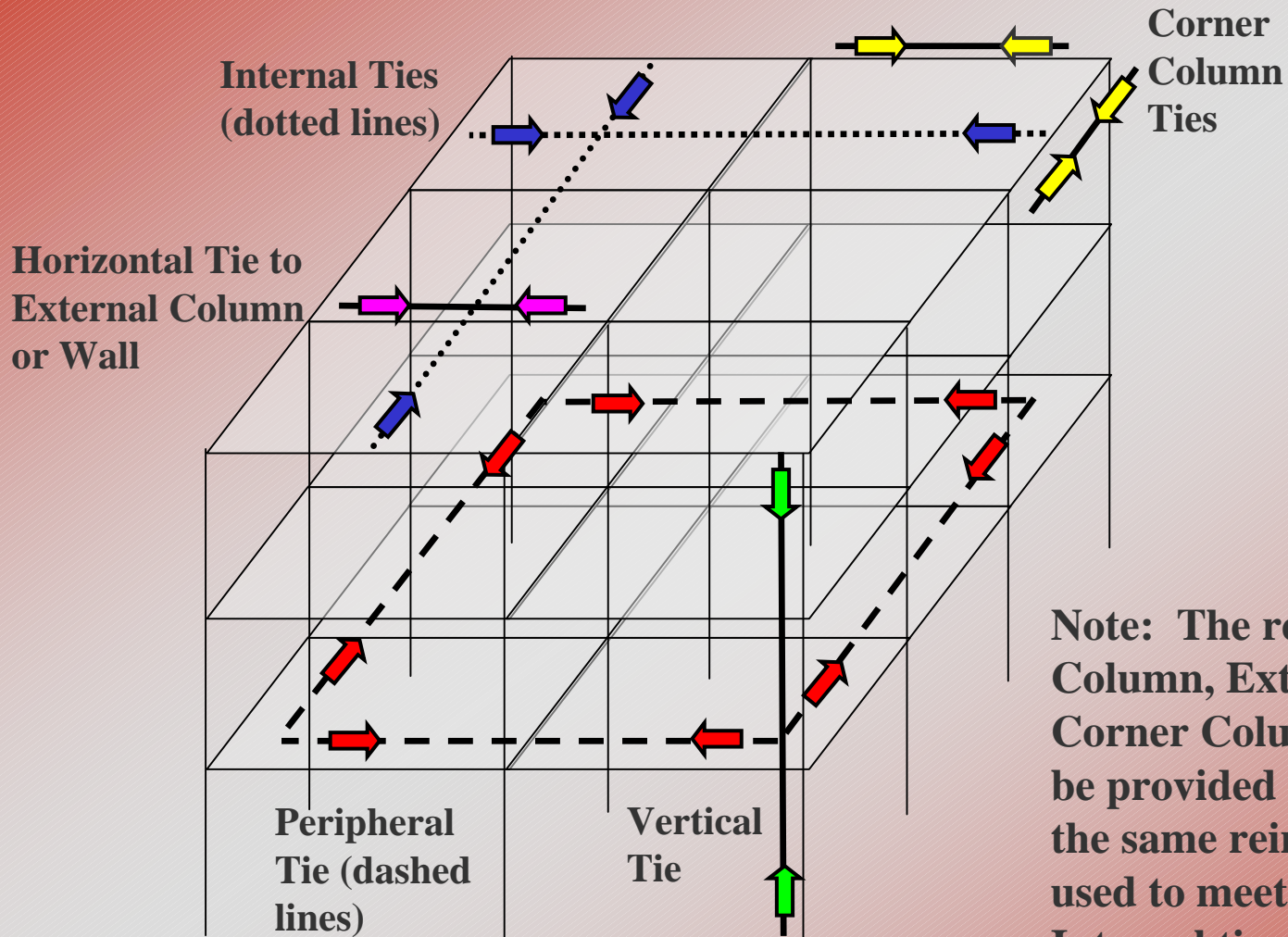
- In the Tie Force approach, the building is mechanically tied together, enhancing continuity, ductility, and development of alternate load paths.
- **Tie forces are typically provided by the existing structural elements and connections that are designed using conventional design procedures to carry the standard loads imposed upon the structure.**

# Tie Forces



- There are several horizontal ties that must be provided: internal, peripheral, and ties to edge columns, corner columns, and walls.
- Vertical ties are required in columns and load-bearing walls.
- Note that these “Tie Forces” are not synonymous with “ties” as defined in ACI.

# Tie Forces



**Note:** The required External Column, External Wall, and Corner Column tie forces may be provided partly or wholly by the same reinforcement that is used to meet the Peripheral or Internal tie requirement.

# Tie Forces



- The load path for peripheral ties must be **continuous** around the plan geometry
- For internal ties, the load path must be **continuous** from one edge to the other.
- Vertical ties must be **continuous** from the lowest level to the highest level.
- Horizontal ties to edge columns and walls **do not have to be continuous, but they must be satisfactorily anchored back into the structure.**

# Tie Forces



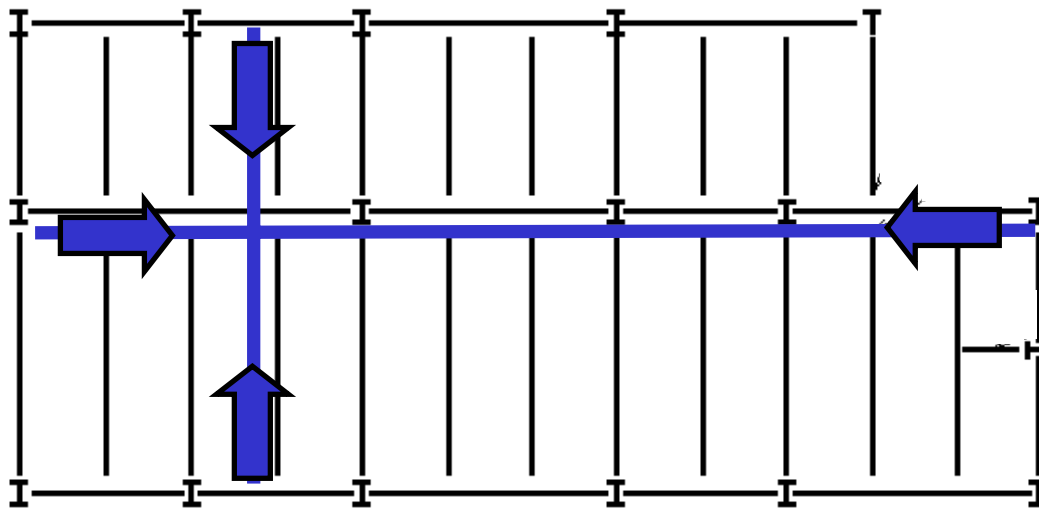
- Along a particular **continuous** load path, different structural elements may be used to provide the required tie strength, providing that they are adequately connected.
  - ◇ For instance, an internal tie force may be provided by a series of beams on a beam line, provided that the connections to the intermediate elements (girders, beams or columns) can provide the required tie strength.

# Tie Forces



- Example: Continuity in a Steel Frame

ALL BEAMS DESIGNED TO ACT AS TIES



# Tie Forces



- Load and Resistance Factor Design for Tie Forces

**Design Tie Strength =  $\Phi R_n \geq$  Required Tie Strength**

where  $\Phi$  = Strength reduction factor

$R_n$  = Nominal Tie Strength of the **element or connection**, calculated with the appropriate material specific code, including over-strength factor  $\Omega$  where applicable.

# Tie Forces



- Design Tie Strength

- ◇ **For the purposes of the PC UFC, all strength reduction factors,  $\Phi$ , are taken as the appropriate material specific code value.**
- ◇ For example, use a strength reduction factor of 0.75 for block shear at a bolted steel connection, as specified in the AISC LRFD code.
- ◇ For some materials (steel and reinforced concrete), an over-strength factor  $\Omega$  can be used to account for the typical excess strength above the design values (i.e., a nominal 36 ksi steel will yield at 45 ksi).

# Tie Forces



- Design Tie Strengths, cont'd
  - ◇ The Design Tie Strengths are considered separately from other forces that are typically carried by each structural element due to live load, dead load, wind load, etc.
  - ◇ In other words, the Design Tie Strength of the element or connection **with no other loads acting** must be greater than or equal to the Required Tie Strength.

# Tie Forces



- Required Tie Strengths

- ◇ The Required Tie Strengths are specific to each material and are provided in Chapters 4 to 8.
- ◇ The Required Tie Strengths are taken from the British Standards.
- ◇ While there is some inconsistency between the use of factored and un-factored loads, the Required Tie Strengths are clearly called out in the UFC for each material.

# Tie Forces



- Structural Elements and Connections With Inadequate Design Tie Strength
  - ◇ If all of the structural elements and connections can be shown to provide the Required Tie Strength, then the tie force requirement has been met.
  - ◇ If any structural element or connection cannot provide a sufficient **vertical** tie force capacity, the designer must either:
    - revise the design to meet the tie force requirements, or,
    - use the Alternate Path method to prove that the structure is capable of bridging over this deficient element.

# Tie Forces



- Structural Elements and Connections With Inadequate Design Tie Strength, cont'd
  - ◇ **Note that the AP method is not applied to structural elements or connections that cannot provide a sufficient horizontal tie force capacity; in this case, the designer must redesign or retrofit the element and connection such that a sufficient capacity is developed.**

# Alternate Path



- The Alternate Path method is used in two situations:
  1. When a structural element or connection cannot provide the required vertical tie force capacity, the designer may use the AP method to prove that the structure can bridge over the deficient element, and,
  2. For structures that require Medium or High Levels of Protection, the AP method must be applied for the removal of specific vertical load-bearing elements which are prescribed in Section 3-2.3.

# Alternate Path



- **For MLOP and HLOP structures, a peer review must be performed and documented for all Alternate Path analyses.**
- The peer reviewers must be independent and qualified organizations who are approved a priori by the building owner.

# Alternate Path



- General

- ◇ The AP method used in the PC UFC incorporates the LRFD philosophy.
- ◇ It is recommended that 3-dimensional models be used to account for potential 3-dimensional effects and to avoid overly conservative solutions.
- ◇ 2-dimensional models can be used provided that the general response and 3-dimensional effects can be adequately idealized.

# Alternate Path



- Three allowable analysis procedures:

- ◇ Linear Static

- The geometric formulation is based on small deformations and the material is treated as linear elastic, with the exception of discrete hinges that may be inserted.

- ◇ Nonlinear Static

- Both the material and geometry are treated as nonlinear.

- ◇ Nonlinear Dynamic

- The material and geometry are nonlinear. A dynamic analysis is performed by instantaneously removing a vertical load-bearing element from the fully loaded structure and analyzing the resulting motion.

# Alternate Path



- Load and Resistance Factor Design for Alternate Path Method

$$\text{Design Strength} = \Phi R_n \geq \text{Required Strength}$$

where  $\Phi$  = Strength reduction factor

$R_n$  = Nominal strength, calculated with the appropriate material specific code, including over-strength factors  $\Omega$  where applicable.

# Alternate Path



- Design Strength
  - ◇ **For the purposes of this UFC, all strength reduction factors  $\Phi$  are taken from the material specific design code, as defined in Chapters 4 to 8.**

# Removal of Load-Bearing Elements



- Removal of Load-Bearing Elements for the Alternate Path Method
  - ◇ Load-bearing elements must be removed from the AP model in two cases:
    - 1) in structures with elements that lack adequate vertical tie force capacity, the deficient element must be removed, and,
    - 2) for MLOP and HLOP structures, locations for element removal are specified to verify that the structure has adequate flexural resistance to bridge over the missing element.

# Removal of Load-Bearing Elements



- Structures With Deficient Vertical Tie Force Capacity
  - ◇ The definition of the size and type of load-bearing element that must be removed is dependent upon the construction material and is presented in Chapters 4 to 8.

# Removal of Load-Bearing Elements



- MLOP and HLOP Framed and Flat Plate Structures
  - ◇ For structures with MLOP and HLOP, multiple AP analyses must be performed, with the load-bearing elements removed from specified plan locations.
  - ◇ The AP method for MLOP and HLOP requires that load-bearing elements be removed **from every floor**, after their plan location is identified.
  - ◇ The main motivation for removing elements from all floors is that DoD facilities could be attacked with direct fire weapons, which could damage a structure at upper floors.

# Removal of Load-Bearing Elements

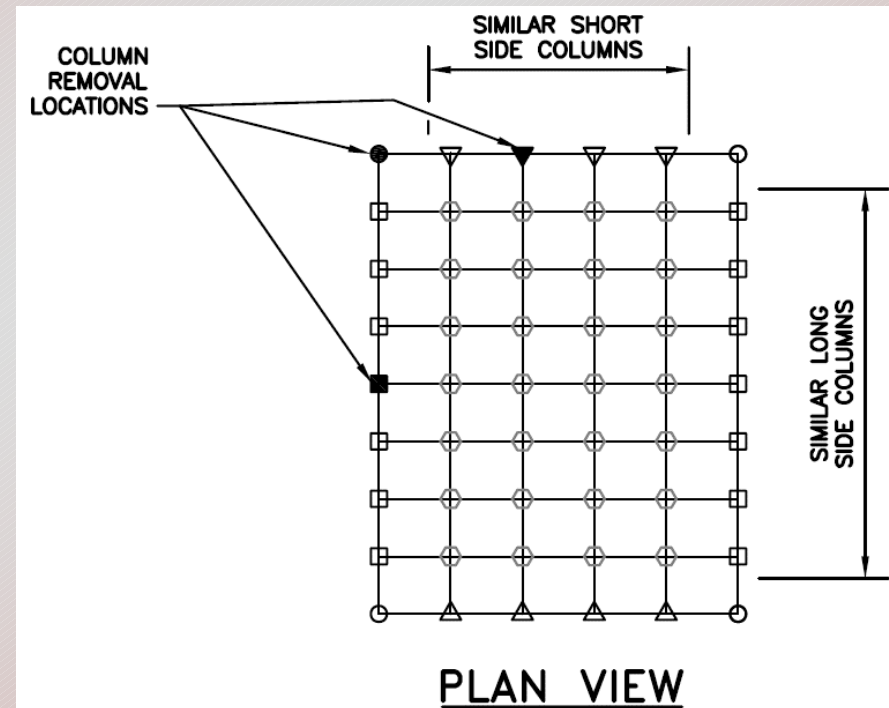


- MLOP and HLOP Framed and Flat Plate Structures, cont'd
  - ◇ Many buildings are susceptible to progressive collapse if the damage initiates at higher elevations (due to the reduced reserve capacity from the fewer number of floors above).
  - ◇ This requirement will motivate the designer to distribute additional strength and ductility to the upper levels.

# Removal of Load-Bearing Elements



- MLOP and HLOP Framed and Flat Plate Structures, cont'd
  - ◇ External Column Removal
    - As a minimum, external columns must be removed near the middle of the short side, near the middle of the long side, and, at the corner of the building, providing that the columns are all “similar” on each side.



# Removal of Load-Bearing Elements



- MLOP and HLOP Framed and Flat Plate Structures, cont'd
  - ◇ External Column Removal, cont'd
    - Columns must also be removed at locations where the plan geometry of the structure changes significantly, such as
      - abrupt decrease in bay sizes and re-entrant corners,
      - at locations where adjacent columns are lightly loaded, the bays have different tributary sizes, or members frame in at different orientations or elevations,
    - Engineering judgment must be used to recognize these critical column locations.

# Removal of Load-Bearing Elements

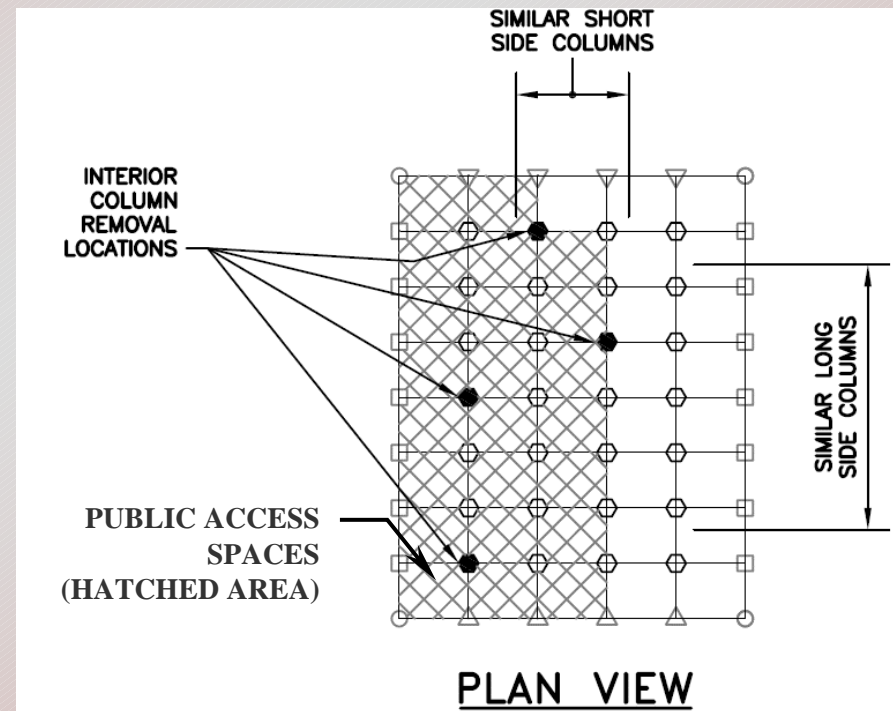


- MLOP and HLOP Framed and Flat Plate Structures, cont'd
  - ◇ External Column Removal, cont'd
    - For each plan location defined for element removal, AP analyses must be performed for each floor, one at a time.
    - If the designer can show that similar structural response is expected for column removal on multiple floors (say, floors 4 through 10), the analysis for these floors can be omitted but the designer must document the justification for not performing these analyses.

# Removal of Load-Bearing Elements



- MLOP and HLOP Framed and Flat Plate Structures, cont'd
  - ◇ Internal Column Removal
    - For structures with underground parking or other uncontrolled public ground floor areas, internal columns must be removed near the middle of the short side, near the middle of the long side and at the corner of the uncontrolled space.



# Removal of Load-Bearing Elements



- MLOP and HLOP Framed and Flat Plate Structures, cont'd
  - ◇ Internal Column Removal, cont'd
    - The removed column extends from the floor of the underground parking area or uncontrolled public ground floor area to the next floor (i.e., a one story height must be removed).
    - Internal columns must also be removed at other critical locations within the uncontrolled public access area, as determined with engineering judgment.
    - **For each plan location, the AP analyses are only performed for the columns on the ground floor or parking area floor and not for all stories in the structure.**

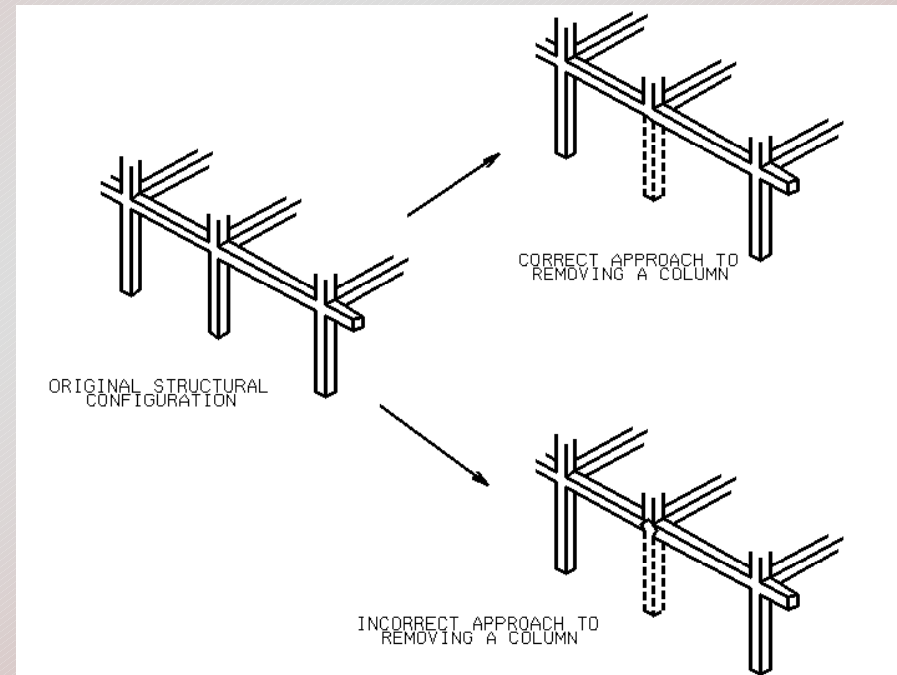
# Removal of Load-Bearing Elements



- MLOP and HLOP Framed and Flat Plate Structures, cont'd

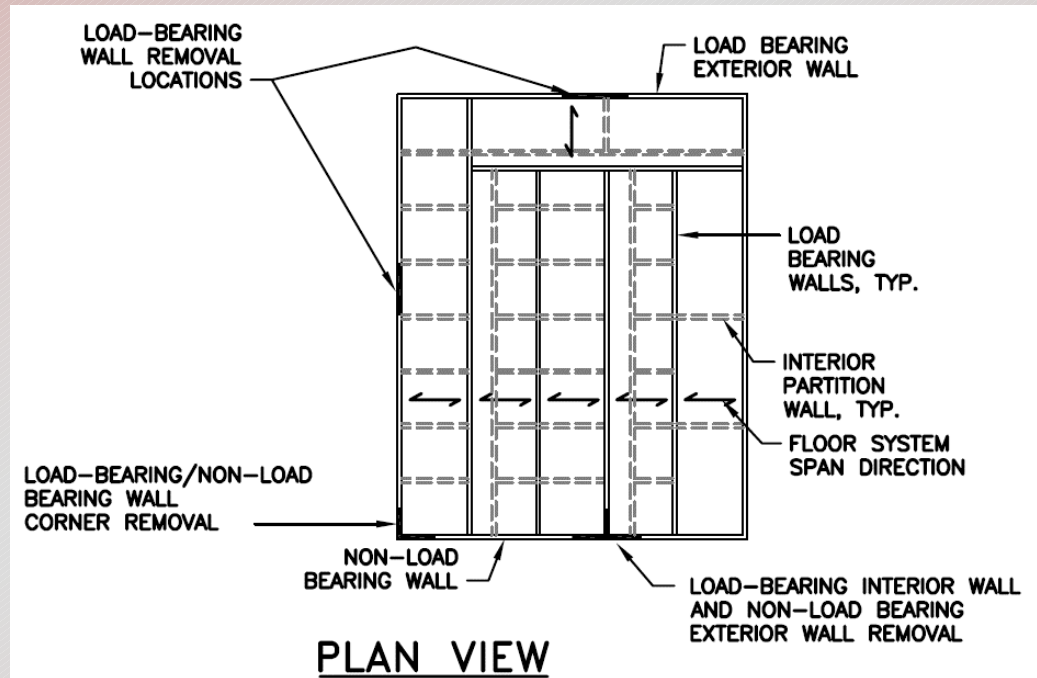
- ◊ Continuity Across Horizontal Elements

- For both external and internal column removal, continuity must be retained across the horizontal elements that connect to the ends of the column.



# Removal of Load-Bearing Elements

- MLOP and HLOP Load-Bearing Wall Structures
  - ◇ External Load-Bearing Walls
    - As a minimum, external load-bearing walls must be removed near the middle of the short side, near the middle of the long side and at the corner of the building.



# Removal of Load-Bearing Elements



- MLOP and HLOP Load-Bearing Wall Structures, cont'd
  - ◇ External Load-Bearing Walls, cont'd
    - Load-bearing walls must also be removed at locations where the plan geometry of the structure changes significantly, such as
      - at an abrupt decrease in bay size and at re-entrant corners,
      - locations where adjacent walls are lightly loaded, the bays have different sizes, and members frame in at different orientations or elevations.
    - Engineering judgment must be used to recognize these critical locations.

# Removal of Load-Bearing Elements

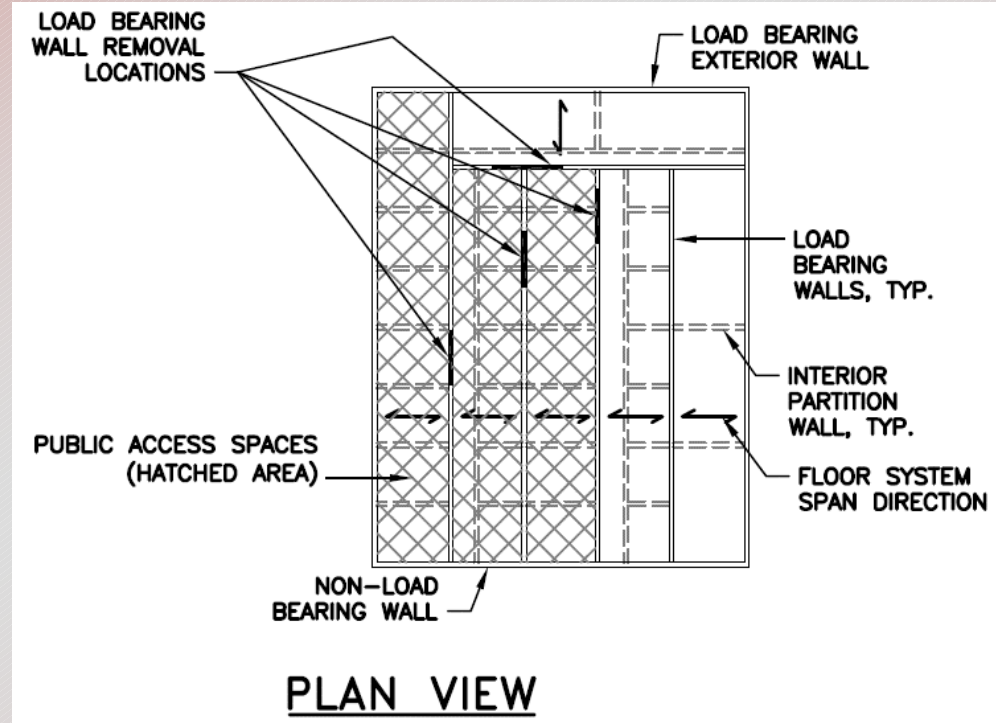


- MLOP and HLOP Load-Bearing Wall Structures, cont'd
  - ◇ External Load-Bearing Walls, cont'd
    - For each plan location defined for element removal, AP analyses must be performed for each floor, one at a time.
    - If the designer can show that similar structural response is expected for wall removal on multiple floors (say, floors 3 through 5), the analysis for these floors can be omitted but the designer must document the justification for not performing these analyses



# Removal of Load-Bearing Elements

- MLOP and HLOP Load-Bearing Wall Structures, cont'd
  - ◇ Internal Load-Bearing Walls
    - For structures with underground parking or uncontrolled public ground floor areas, internal load-bearing walls must be removed near the middle of the short side, near the middle of the long side and at the corner of the uncontrolled space.



# Removal of Load-Bearing Elements



- MLOP and HLOP Load-Bearing Wall Structures, cont'd
  - ◇ Internal Load-Bearing Walls, cont'd
    - The removed wall extends from the floor of the underground parking area or uncontrolled public ground floor area to the next floor (i.e., a one story height must be removed).
    - Internal load-bearing walls must also be removed at other critical locations within the uncontrolled public access area, as determined with engineering judgment.
    - For each plan location, the AP analyses are only performed for the load-bearing walls on the ground floor or parking area floor and not for all stories in the structure.

# Removal of Load-Bearing Elements



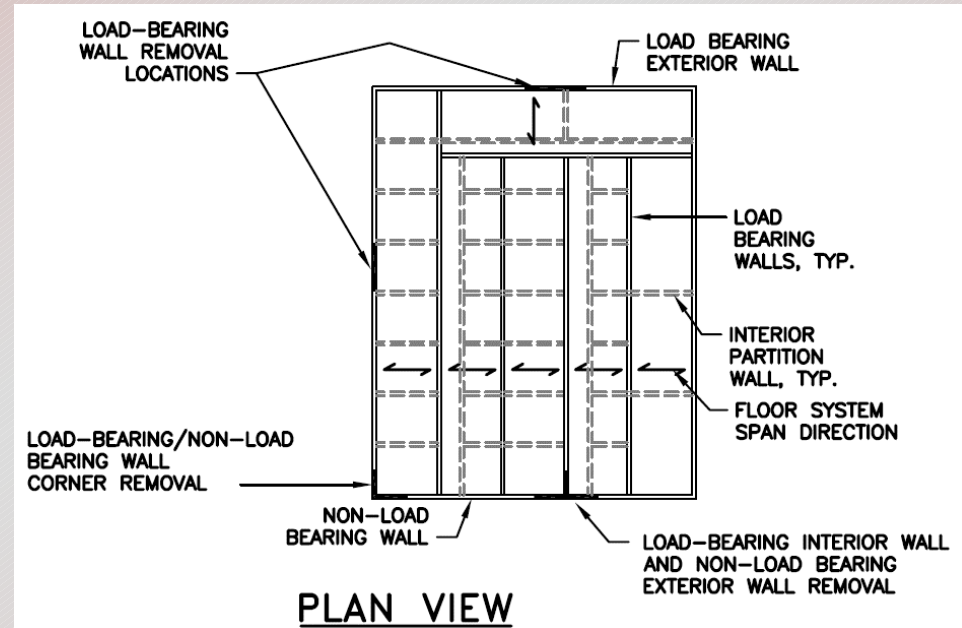
- MLOP and HLOP Load-Bearing Wall Structures, cont'd
  - ◇ Length of Removed Load-Bearing Walls
    - For load-bearing walls on the sides of the building, the length of removed wall must be equal to two times the wall height but not less than the distance between expansion or control joints.
    - For load-bearing walls at the corner, a width of wall equal to the wall height in each direction but not less than the distance between expansion or control joints must be removed.

# Removal of Load-Bearing Elements

- MLOP and HLOP Load-Bearing Wall Structures, cont'd

- ◊ Length of Removed Load-Bearing Walls

- For the situation in which the external wall is not load-bearing but the intersecting internal wall is load-bearing, a width of the load-bearing wall equal to the wall height must be removed.



- The width of any removed wall may be reduced to the actual distance between vertical intersecting elements that are load-bearing and are structurally connected to the wall being removed.

# Factored Loads



- Nonlinear Dynamic Analysis Load Case (3-2.4.1)
  - Per ASCE 7-02, Section C2.5, Load Combinations for Extraordinary Events, apply the following factored load combination to the entire structure:

$$(0.9 \text{ or } 1.2) D + (0.5 L \text{ or } 0.2 S) + 0.2 W$$

where

- D = Dead load (kN/m<sup>2</sup> or lb/ft<sup>2</sup>)
- L = Live load (kN/m<sup>2</sup> or lb/ft<sup>2</sup>)
- S = Snow load (kN/m<sup>2</sup> or lb/ft<sup>2</sup>)
- W = Wind load, as defined for the Main Wind Force-Resisting System in Section 6 of ASCE 7-02 (kN/m<sup>2</sup> or lb/ft<sup>2</sup>)

# Factored Loads



- Linear and Nonlinear Static Analysis Load Case
  - For Linear and Nonlinear Static analyses of all construction types, apply the following *amplified* factored load combination to those bays immediately adjacent to the removed element and at all floors above the removed element.

$$2.0 [ (0.9 \text{ or } 1.2) D + (0.5 L \text{ or } 0.2 S) ] + 0.2 W$$

# Factored Loads

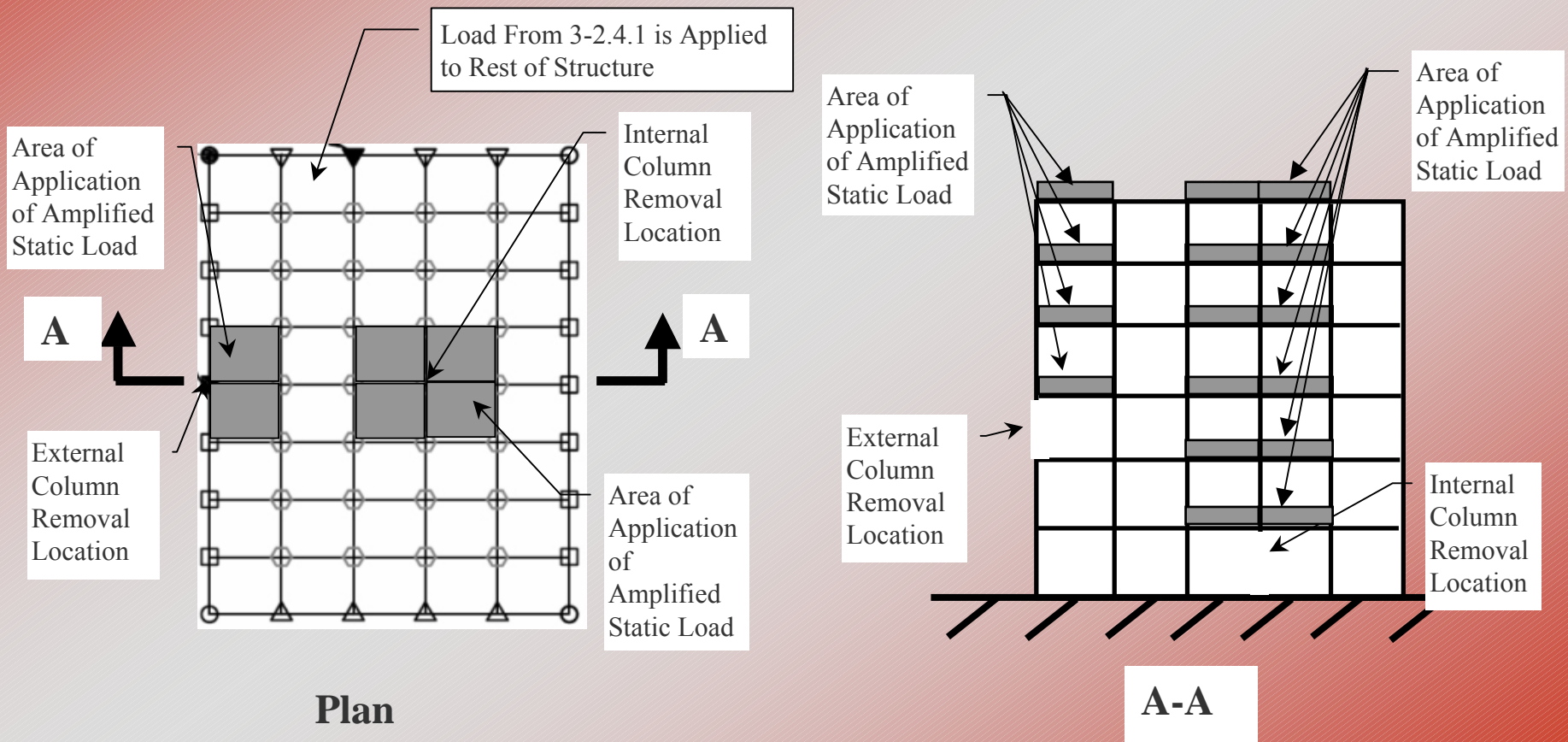


- Linear and Nonlinear Static Analysis Load Case, cont'd
  - For the rest of the structure, apply the Nonlinear Dynamic load combination (from 3-2.4.1).
  - For load-bearing wall systems, the adjacent bay is defined as the plan area that spans between the removed wall and the nearest load-bearing walls.

# Factored Loads



- Linear and Nonlinear Static Load Locations for External and Internal Column Removal



# Factored Loads



- Linear and Nonlinear Static Analysis Load Case, cont'd
  - The factor of 2.0 acting on the Dead, Live and Snow Loads is used to account for the localized inertial effects due to the loss of vertical support over a short, finite period of time.
  - The factor 2.0 is used in the GSA guidelines and has been validated as conservative.

# Factored Loads

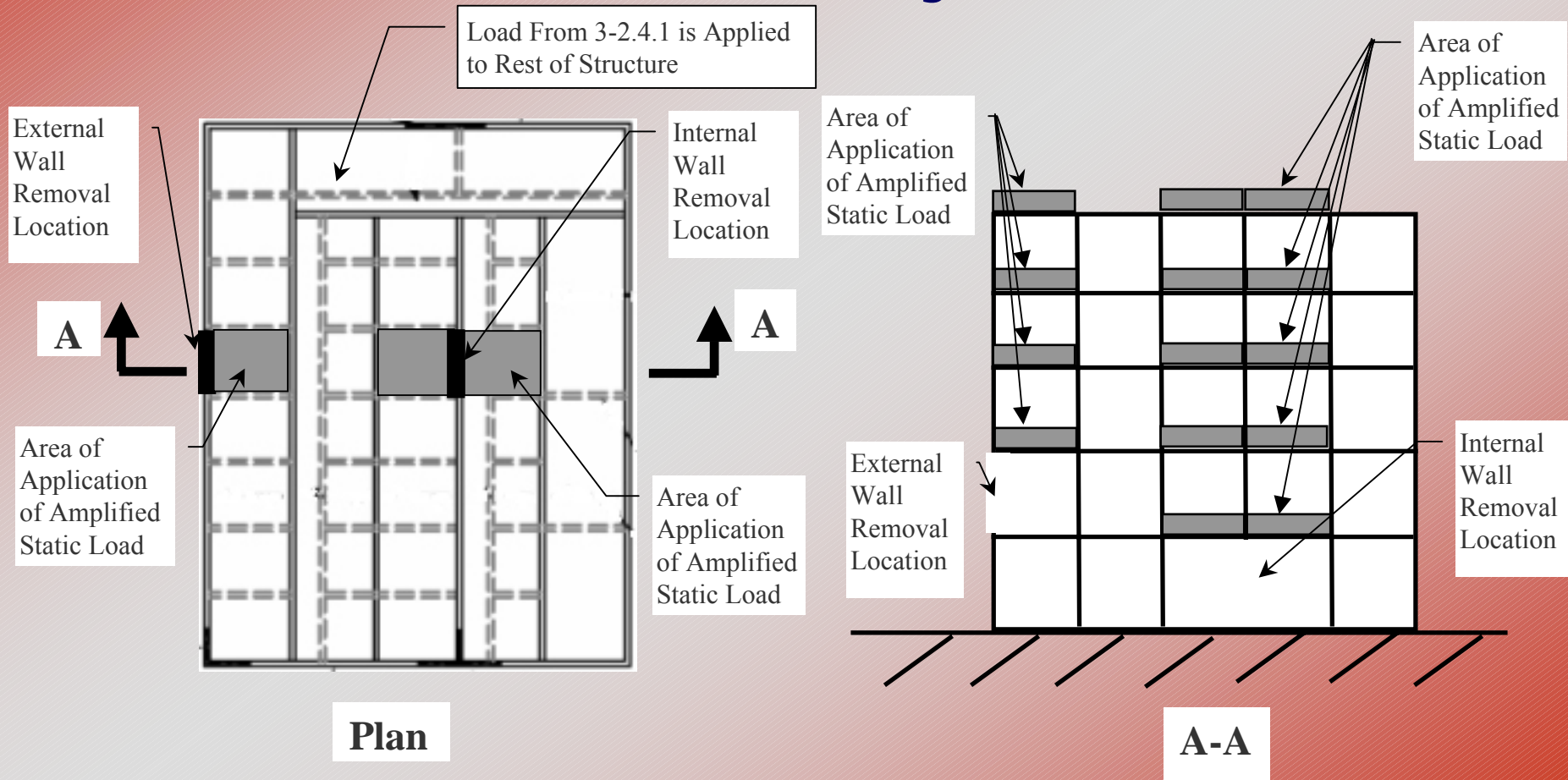


- Linear and Nonlinear Static Analysis Load Case, cont'd
  - The increased loads are only applied to the bays adjacent to and above the removed load-bearing element.
  - The increased loads are limited to these areas as they are most likely to experience significant inertial loading, whereas the rest of the structural will experience much smaller motion.

# Factored Loads



- Linear and Nonlinear Static Load Locations for External and Internal Load-Bearing Wall Removal



# Alternate Path



- Loads Associated with Failed Elements
  - ◇ The internal forces or deformation in a structural element or connection may be shown to exceed the acceptability criteria.
  - ◇ If so, the element is considered to be failed and is removed from the model.
  - ◇ For a Linear or Nonlinear Static analysis;
    - Apply the loads from the failed element (which are already doubled) to the section of the structure directly below the failed element, before the analysis is re-run or continued.

# Alternate Path



- Loads Associated with Failed Elements, cont'd
  - ◇ For a Nonlinear Dynamic analysis:
    - Double the loads from the failed element and apply them instantaneously to the section of the structure directly below the failed element, before the analysis continues.
  - ◇ Apply the loads from the area supported by the failed element to an area equal to or smaller than the area from which they originated.

# Alternate Path



- Material Properties

- ◇ Material properties, such as yield stress, failure stress, etc, must be taken in accordance with the requirements of the appropriate material specific code.
- ◇ For some construction types, an over-strength factor  $\Omega$  or time effect factor  $\lambda$  is permitted, to account for the typical over-strengths expected for that material.
- ◇ The appropriate factors for each material are given in Chapters 4 to 8.

# Alternate Path



- Damage Limits

- ◇ In AP analysis with any of the three methods (Linear Static, Nonlinear Static, and Nonlinear Dynamic), the extent of damage will be quantified during the analysis and at the end of the analysis.
- ◇ Damage Limits are used to define when the extent of damage is unacceptable.
- ◇ The Damage Limits given in the UFC were taken from the Interim Technical Guidance and similar values are used by the British.

# Alternate Path



- Damage Limits, cont'd
  - ◇ Damage Limits for Removal of **External** Column or Load-Bearing Wall
    - For the removal of a wall or column on the external envelope of a building, the Damage Limits require that the collapsed area of the floor directly above the removed element must be less than the smaller of 70 m<sup>2</sup> (1500 ft<sup>2</sup>) or 15% of the total area of that floor and the floor directly beneath the removed element should not fail.
    - Any collapse must not extend beyond the bays immediately adjacent to the removed element.

# Alternate Path



- Damage Limits, cont'd
  - ◇ Damage Limits for Removal of **Internal** Column or Load-Bearing Wall
    - For the removal of an internal wall or column of a building, the Damage Limits require that the collapsed area of the floor directly above the removed element must be less than the smaller of 140 m<sup>2</sup> (3000 ft<sup>2</sup>) or 30% of the total area of that floor, and the floor directly beneath the removed element should not fail.
    - In addition any collapse must not extend beyond the bays immediately adjacent to the removed element.

# Acceptability Criteria



- The Acceptability Criteria for structural elements and connections consist of **strength requirements** and **deformation limits**.
  - ◇ The moments, axial forces, and shears that are calculated for the elements and connections in each AP analysis are the Required Strengths, as defined in the LRFD equation.
  - ◇ These Required Strengths must be compared to the Design Strengths of each element and connection, as shown generically in Table 3-1.

## Acceptability Criteria for Elements and Connections and Subsequent Action for AP Model

Structural Behavior	Acceptability Criteria	Subsequent Action for Violation of Criteria
Element Flexure	Flexural Design Strength <sup>A</sup> (based on compactness, bracing, amount and type of reinforcing steel, etc)	<p>For elements that can carry moment after the peak moment is reached: In Linear Static analysis, insert hinge at appropriate offset from connection and apply a constant moment on both sides of the hinge (Figure 3-9). For Nonlinear Static and Dynamic analysis, the model and software must automatically incorporate nonlinear flexural response.</p> <p>For elements that fail upon reaching peak strength, remove failed element from model and redistribute the loads per Section 3-2.4.3.</p>
Element Combined Axial and Flexure	Interaction Equations Using Axial and Flexural Design Strengths <sup>A</sup>	Remove failed element from model and redistribute the loads per Section 3-2.4.3.
Element Shear	Shear Design Strength <sup>A</sup>	Remove failed element from model and redistribute the loads per Section 3-2.4.3.
Connections	Connection Design Strength <sup>A</sup>	Remove connection.
Deformation	Deformation Limits, defined for each material in Chapters 4 to 8.	Remove failed element from model and redistribute the loads per Section 3-2.4.3.

# Acceptability Criteria



- The calculated deflection and rotations for elements and connections in the AP model must also be compared against the deformation limits that are specific to each material type.
- If any structural element or connection violates an acceptability criteria (strength or deformation), modifications must be made to the model before it is re-analyzed, as discussed in more detail in the following.

# Acceptability Criteria



- Flexural Resistance

- ◇ The flexural acceptability criteria is based on the the flexural design strength of the structural element, including the strength reduction factor  $\Phi$ , and the over-strength factor  $\Omega$ .
- ◇ In calculating the flexural design strength, the designer **must account for the material-specific factors that can reduce the flexural design strength**, such as compactness and lateral bracing for structural steel, amount of rebar in reinforced concrete, etc.

# Acceptability Criteria



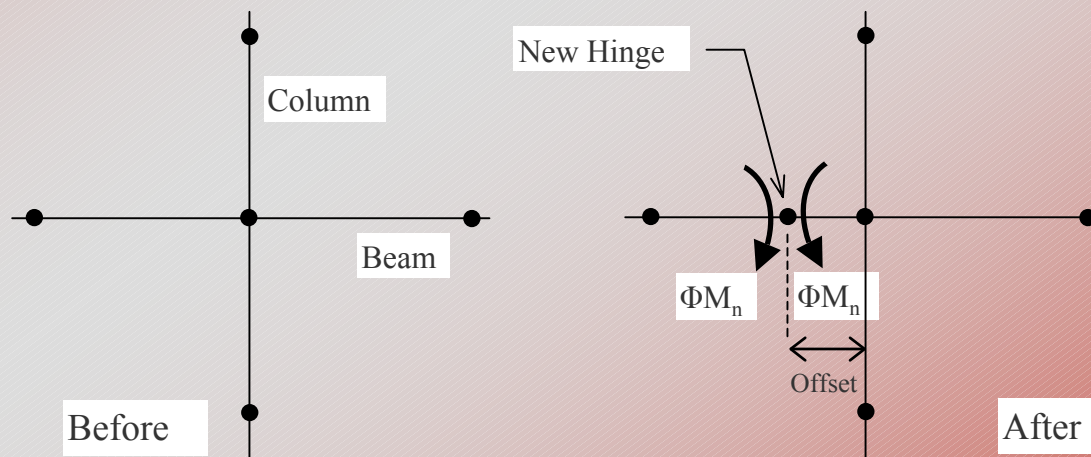
- Flexural Resistance, cont'd
  - ◇ In Linear Static models, for structural elements that can sustain a constant moment while undergoing continued deformation, an effective plastic hinge is added to the model.
  - ◇ A discrete hinge is inserted into the member at the location of yielding.
  - ◇ Two constant moments must be applied, one at each side of the new hinge, in the appropriate direction for the acting moment.

# Acceptability Criteria



- Flexural Resistance, cont'd

- ◇ The designer must determine the location of the plastic hinge through engineering analysis and judgment or with the guidance provided for the particular construction type.



# Acceptability Criteria



- Flexural Resistance, cont'd
  - ◇ In Nonlinear Static and Dynamic models, the software must have the ability to adequately represent the nonlinear flexural response, after the internal moment (Required Strength) reaches the peak moment (Design Strength) of the element.

# Acceptability Criteria



- Flexural Resistance, cont'd
  - ◇ For structural elements that fail when the peak moment is reached and in all three model types (Linear Static, Nonlinear Static and Nonlinear Dynamic), the element must be removed when the internal moment exceeds the flexural design strength.
  - ◇ The loads associated with the failed element must be redistributed as discussed earlier, before the analysis continues.

# Acceptability Criteria



- Combined Axial and Flexural Resistance
  - ◇ The acceptability criteria for elements undergoing combined axial and bending loads is based on the provisions given in the material-specific design code.
  - ◇ For elements that are controlled by flexure, follow the procedure outlined in Section 3-2.7.1 (just given).
  - ◇ For elements controlled by buckling, remove the failed element from the model and redistribute the loads per Section 3-2.4.3. The loads from a failed element must be redistributed.

# Acceptability Criteria

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- Shear Resistance
  - ◇ If the shear design strength is exceeded for any construction type, the member must be removed and the loads from that element must be redistributed.

# Acceptability Criteria



- Connections

- ◇ If the deformation limits or the design strength for any connection failure mode is exceeded, the connection must be removed.
- ◇ If the connections at both ends of an element have failed, the loads from that element must be redistributed.

# Acceptability Criteria



- Connections, cont'd
  - ◇ The designer must use the guidance provided in the material-specific design codes or other sources to develop connection details that can provide the required strength, while undergoing potentially large deformations.
  - ◇ In a number of the material-specific design codes, provisions for seismic design are presented, including connection details; the designer must incorporate this information, as appropriate, in designing connections.

# Acceptability Criteria



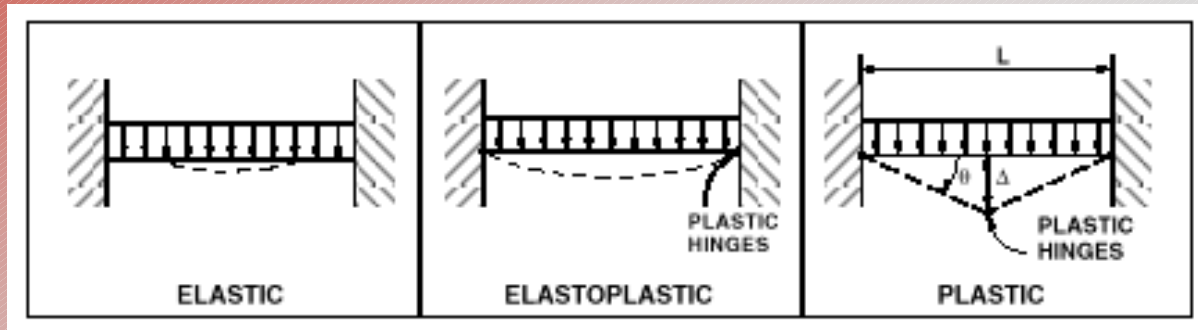
- Deformation Limits

- ◇ Deformation limits are defined in terms of the deflections and rotations in the structural elements, connections and frame.
- ◇ Excessive deflections or rotations imply that the element or portion of the frame has deformed to the point that it can no longer carry load.
- ◇ Calculation of rotations for members, connections, and frames is illustrated on the next slide.
- ◇ If an element or connection exceeds a deformation limit, remove it from the model.

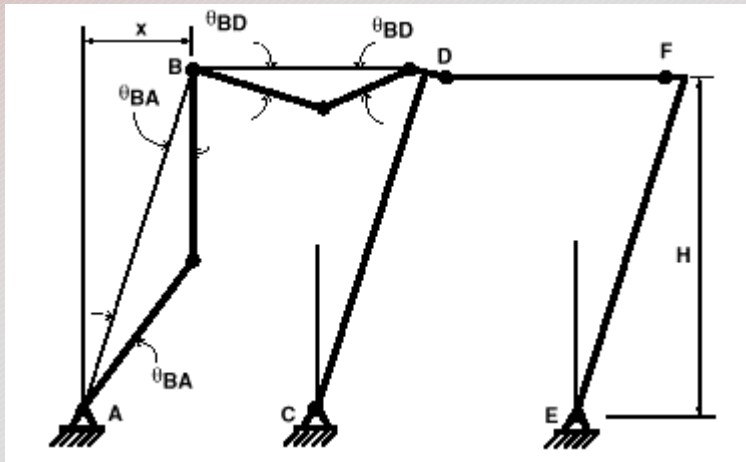
# Acceptability Criteria



- Deformation Limits, cont'd



Measurement of  
Hinge Rotation  $\theta$   
After Formation of  
Plastic Hinges



Sidesway and Member End  
Rotations ( $\theta$ ) for Frames

# Analysis Procedures



- Linear Static Analysis Procedure
  - ◇ Note that a second order or P- $\Delta$  analysis is required.
    1. For AP analyses for load-bearing elements that do not have adequate vertical tie force capacity, remove the element from the structural model in accordance with the material-specific requirements given in Chapters 4 to 8. For AP analyses of MLOP and HLOP structures, remove the column or load-bearing wall per Sections 3-2.3.2 and 3-2.3.3.
    2. Apply the loads defined in Section 3-2.4.2.

# Analysis Procedures



- Linear Static Analysis Procedure, cont'd
  3. After the analysis is performed, compare the predicted element and connection forces and deformations against the acceptability criteria. To demonstrate compliance with the acceptability criteria, the designer may use a software package with modules that perform building code checks, providing the modules can be tailored to check the criteria in Table 3-1. The designer must confirm that all material-specific code provisions for bracing, compactness, flexural-axial interaction, etc, are met.

# Analysis Procedures



- Linear Static Analysis Procedure, cont'd
  4. If none of the structural elements or connections violates the acceptability criteria, the analysis is complete and satisfactory resistance to progressive collapse has been demonstrated. If any of the structural elements or connections violate the acceptability criteria, perform the following procedure in Steps A through E.

# Analysis Procedures



- Linear Static Analysis Procedure, cont'd
  - 4, cont'd
    - A. Modify the geometry or material properties of the model, per Table 3-1 (i.e., remove elements and/or insert hinges and constant moments).
    - B. If an element was shown to fail, redistribute the element's loads per Section 3-2.4.3.
    - C. Re-analyze this modified model and applied loading.

# Analysis Procedures



- Linear Static Analysis Procedure, cont'd

- 4, cont'd

D. At the end of the re-analysis, assess the resulting damaged state and compare with the damage limits in Section 3-2.6. If the damage limits are violated, re-design and re-analyze the structure, starting with Step 1. If the damage limits are not violated, compare the resulting internal forces and deformation of each element and connection with the acceptability criteria

# Analysis Procedures



- Linear Static Analysis Procedure, cont'd
  5. If any of the acceptability criteria are violated in the new analysis, repeat this process (Steps A through E), until the damage limits are violated or there are no more violations of the acceptability criteria. If the damage limits are violated, re-design and reanalyze the structure, starting with Step 1. If the damage limits are not violated and no new elements failed the acceptability criteria, then the design is adequate.

# Analysis Procedures



- Non-Linear Static Analysis Procedure
  1. For AP analyses for load-bearing elements that do not have adequate vertical tie force capacity, remove the element from the structural model in accordance with the material-specific requirements given in Chapters 4 to 8. For AP analyses of MLOP and HLOP structures, remove the column or load-bearing wall per Sections 3-2.3.2 and 3-2.3.3.

# Analysis Procedures



- Non-Linear Static Analysis Procedure, cont'd
  2. Apply the loads using a load history that starts at zero and is increased to the final values defined in Section 3-2.4.2. Apply at least 10 load steps to reach the total load. The software must be capable of incrementally increasing the load and iteratively reaching convergence before proceeding to the next load increment.

# Analysis Procedures



- Non-Linear Static Analysis Procedure, cont'd
  3. As the analysis is performed, compare the predicted element and connection forces and deformations against the acceptability criteria that are shown generically in Table 3-1. To demonstrate compliance with the acceptability criteria, the designer may use a software package with modules that perform building code checks, providing the modules can be tailored to check the criteria in Table 3-1. The designer must confirm that all material-specific code provisions for bracing, compactness, flexural-axial interaction, etc, are met.

# Analysis Procedures



- Non-Linear Static Analysis Procedure, cont'd
  4. If none of the structural elements or connections violates the acceptability criteria during the loading process, the analysis is complete and satisfactory resistance to progressive collapse has been demonstrated. If any of the structural elements or connections violate the acceptability criteria, perform the following procedure (Steps A through E):

# Analysis Procedures



- Non-Linear Static Analysis Procedure, cont'd

- ◇ 4, cont'd

- A. At the point in the load history when the element or connection fails the acceptability criteria, remove the element or connection, per Table 3-1.
- B. If an element was shown to fail, redistribute the element's loads per Section 3-2.4.3.
- C. Restart the analysis from the point in the load history at which the element or connection failed and the model was modified. Increase the load until the maximum load is reached or until another element or connection violates the acceptability criteria.

# Analysis Procedures



- Non-Linear Static Analysis Procedure, cont'd

- ◇ 4, cont'd

- D. At each point at which the analysis is halted, check the predicted damage state against the damage limits in Section 3-2.6. If the damage limits are violated, re-design and re-analyze the structure, starting with Step 1.

# Analysis Procedures



- Non-Linear Static Analysis Procedure, cont'd

- ◇ 4, cont'd

- E. If the damage limits are not violated and the total load has been applied, the design is adequate. If the damage limits are not violated but one of the acceptability criteria was violated in the re-started analysis, repeat this process (Steps A through E), until the total load is applied or the damage limits are violated.

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure
  1. Distribute the mass of the structure throughout the model in a realistic manner; lumped masses are not allowed, unless to represent mechanical equipment, pumps, architectural features, and similar items. Distribute mass along beams and column as mass per unit length; for slabs and floors, represent the mass as mass per unit area. If any portion of the structure is represented by solid elements, distribute the mass as mass per unit volume

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  2. Prior to the removal of the load-bearing element, bring the model to static equilibrium under the loads from Section 3-2.4.1; the process for reaching equilibrium under gravity loads will vary with analysis technique

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  3. With the model stabilized, remove the appropriate load-bearing element instantaneously. For AP analyses for load-bearing elements that do not have adequate vertical tie force capacity, remove the element in accordance with the material-specific requirements given in Chapters 4 to 8. For AP analyses of MLOP and HLOP structures, remove the column or load-bearing wall per Sections 3-2.3.2 and 3-2.3.3.

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  4. Continue the dynamic analysis until the structure reaches a steady and stable condition (i.e., the displacement history of the model reaches a near constant value, with very small oscillations and all material and geometric nonlinear processes have halted).

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  5. During or after the analysis, compare the predicted element and connection forces and deformations against the acceptability criteria that are shown generically in Table 3-1. To demonstrate compliance with the acceptability criteria, the designer may use a software package with modules that perform building code checks, providing the modules can be tailored to check the criteria in Table 3-1. The designer must confirm that all material-specific code provisions for bracing, compactness, flexural-axial interaction, etc, are met.

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  6. If none of the structural elements or connections violates the acceptability criteria during the dynamic motion of the structure, the analysis is complete and satisfactory resistance to progressive collapse has been demonstrated. If any of the structural elements or connections violate the acceptability criteria, perform the following procedure (Steps A through E).

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  - ◇ 6, cont'd
    - A. At the point in the load history when the element or connection fails the acceptability criteria, instantaneously remove the element or connection from the model, per Table 3-1.
    - B. If an element was shown to fail, redistribute the element's loads per Section 3-2.4.3.

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  - ◇ 6, cont'd
    - C. Restart the analysis from the point in the load history at which the element or connection failed and the model was modified. Continue the analysis until the structural model stabilizes or until another element or connection violates the acceptability criteria.

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  - ◇ 6, cont'd
    - D. For each time at which the analysis is halted due to violation of an element acceptability criteria, the damage limits must be checked. If the damage limits are violated, stop the analysis and re-design and re-analyze the structure, starting with Step 1.

# Analysis Procedures



- Non-Linear Dynamic Analysis Procedure, cont'd
  - ◇ 6, cont'd
    - E. If the damage limits are not violated and the structural model stabilizes, the design is adequate. If the damage limits are not violated but one of the acceptability criteria was violated in the re-started analysis, repeat this process (Steps A through E) until the structure reaches a stable condition or the damage limits are violated.

# Alternate Path

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## Questions/Comments?